PIRAMID

A Quantitative Risk-based Approach to Integrity Maintenance Planning and Design Optimization for Offshore Pipelines

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Background to the PIRAMID Project

- **A Multi-year Joint Industry Program**

- **Sponsors**
  - **BC Gas Utility**
  - **Enbridge Inc. (Interprovincial)**
  - **Foothills Pipe Lines**
  - **Kinder Morgan (KN Energy)**
  - **Southern California Gas**
  - **TransCanada Pipelines**
  - **Gas Research Institute**
  - **Canadian Geological Survey**
  - **U.S. Minerals Management Service**

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Develop Models and Software to:

- **Make optimal maintenance decisions**
  - **Ensure acceptable risk levels**
  - **At the lowest possible cost**

- **Explain rationale behind decisions**
  - **Internally within company**
  - **Externally to regulators and the public**

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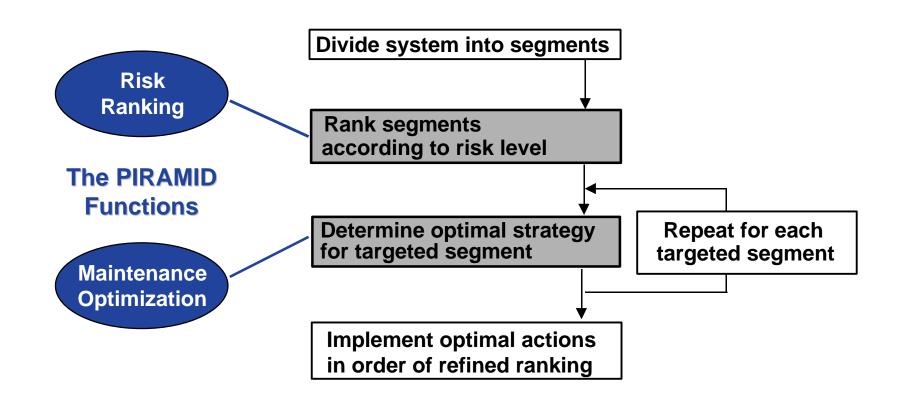
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Issues To Be Addressed

- **What is the operating risk associated with the pipeline in its present state**

- **What effect would each candidate maintenance strategy have on the operating risk**

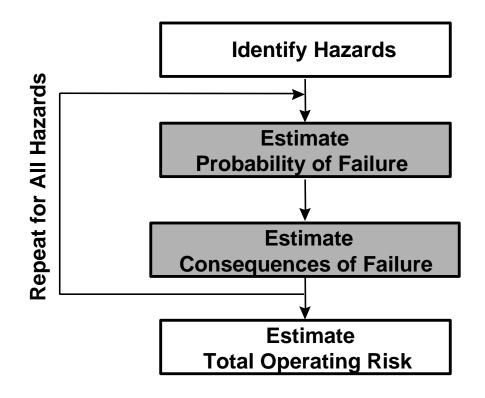- **What is the lowest cost maintenance option that meets acceptable safety & environmental constraints**

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PIRAMID Functions

Risk Ranking

The PIRAMID Functions

Maintenance Optimization

Divide system into segments

Rank segments according to risk level

Determine optimal strategy for targeted segment

Repeat for each targeted segment

Implement optimal actions in order of refined ranking

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Risk Ranking

For each Segment in System

```
                    ┌─────────────────────────────┐
                    │      Identify Hazards        │
                    └─────────────────────────────┘
                                   │
  ┌─────────────────────────────►  ▼
  │                 ┌─────────────────────────────┐
R │                 │          Estimate           │
e │                 │    Probability of Failure    │
p │                 └─────────────────────────────┘
e │                               │
a │                               ▼
t │                 ┌─────────────────────────────┐
  │                 │          Estimate           │
f │                 │   Consequences of Failure    │
o │                 └─────────────────────────────┘
r │                               │
  │                               ▼
A │                 ┌─────────────────────────────┐
l │                 │          Estimate           │
l │                 │   Total Operating Risk       │
  │                 └─────────────────────────────┘
H │
a │
z │
a │
r │
d │
s │
```

Repeat for All Hazards

Identify Hazards

Estimate Probability of Failure

Estimate Consequences of Failure

Estimate Total Operating Risk

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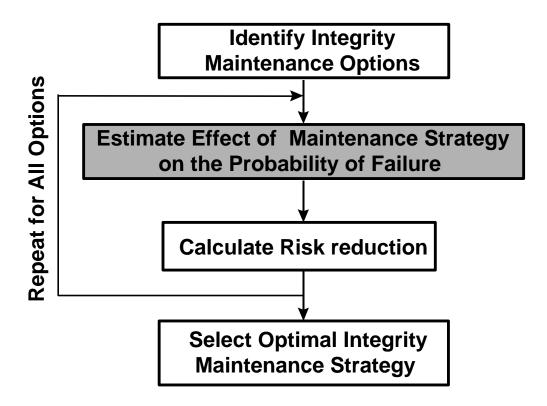
Maintenance Optimization

For each Targeted Segment

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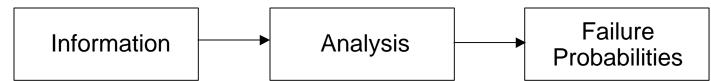technology creates advantage

PIRAMID Features

- **Quantitative approach**
- **Extensive use of engineering models**
- **Calculates total risk**
  - financial
  - safety
  - environmental
- **Validated by real pipeline data**

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Probability Estimation Approaches

General

| Information | → | Analysis | → | Failure Probabilities |

Adjusted historical failure rate method

| Failure rates | → | Adjustment factors | → | Failure Probabilities |
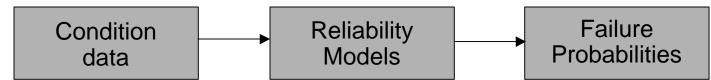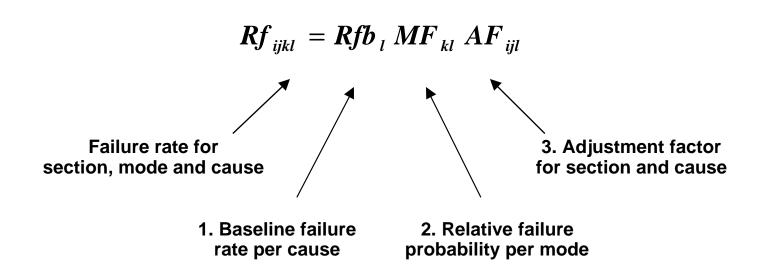
Structural reliability method

| Condition data | → | Reliability Models | → | Failure Probabilities |

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Adjusted Historical Failure Rate Method

$$Rf_{ijkl} = Rfb_l \, MF_{kl} \, AF_{ijl}$$

Failure rate for
section, mode and cause

3. Adjustment factor
for section and cause

1. Baseline failure
rate per cause

2. Relative failure
probability per mode

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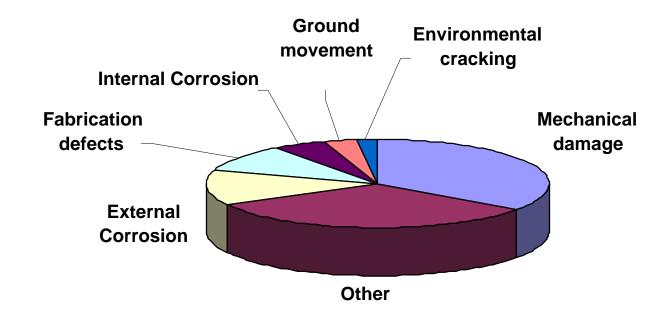
Baseline Failure Rates by Cause

Failure Rates by Mode

Failure Cause	Mode Factor		
	small leak	large leak	rupture
Metal Loss Corrosion	???	???	???
Mechanical Damage	???	???	???
Ground Movement	???	???	???
Cracks	???	???	???
Other Causes	???	???	???

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Probability Adjustment Factors

E.g. - for External Corrosion

$$AF = f(A, t, T) \, F_{SC} \, F_{CP} \, F_{CT} \, F_{CC}$$

Adjustment factor

Line age

Wall thickness

Operating temperature

Soil corrosivity factor

Cathodic protection factor

Coating type factor

Coating condition factor

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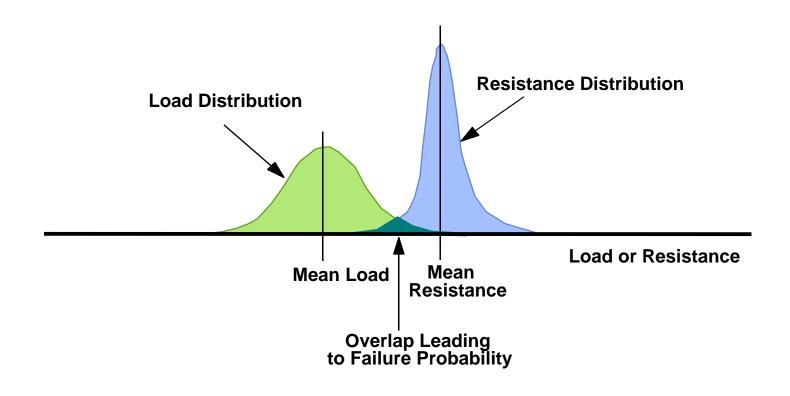
Adjusted Failure Rates - Summary

- **Simple models utilizing**

  - **Statistical data**

  - **Engineering analysis**

  - **Judgment**

- **Suitable for segment ranking**

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Structural Reliability Approach

Load Distribution

Resistance Distribution

Mean Load

Mean Resistance

Overlap Leading to Failure Probability

Load or Resistance

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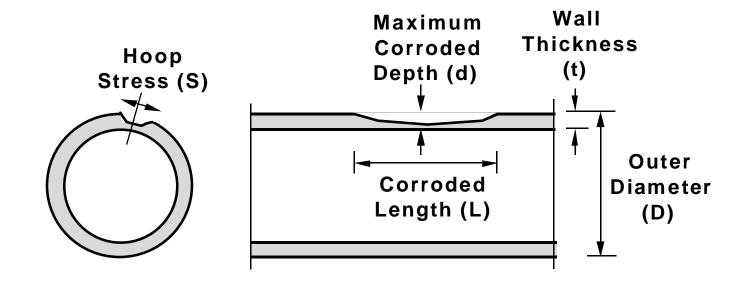
Application to External Corrosion

Hoop Stress (S)

Maximum Corroded Depth (d)

Wall Thickness (t)

Corroded Length (L)

Outer Diameter (D)
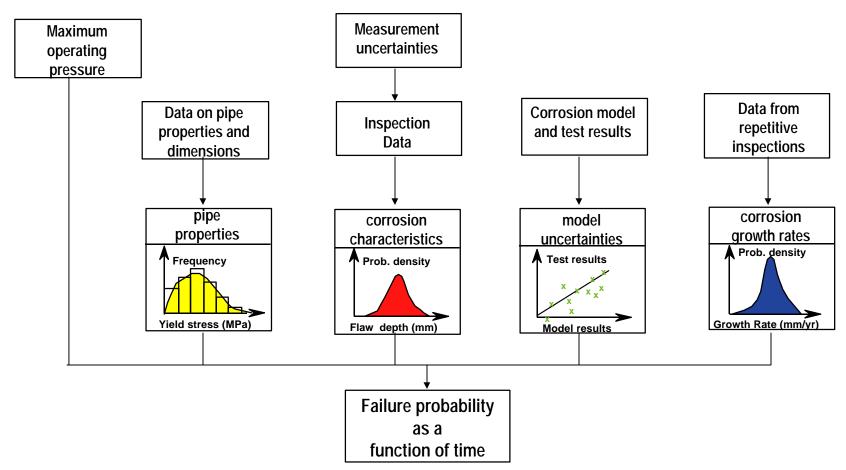
Failure rate / km = No. Defects per km x Failure probability per defect

Failure Probability per Defect

Maximum operating pressure

Measurement uncertainties

Data on pipe properties and dimensions

Inspection Data

Corrosion model and test results

Data from repetitive inspections

pipe properties — Frequency / Yield stress (MPa)

corrosion characteristics — Prob. density / Flaw depth (mm)

model uncertainties — Test results / Model results

corrosion growth rates — Prob. density / Growth Rate (mm/yr)

Failure probability as a function of time

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Probability of Failure Versus Time

Effect of Maintenance

- **Mitigation philosophy**
  - Find and eliminate defects before they reach critical size

- **Maintenance options**
  - Inspection and repair
  - Hydro-testing
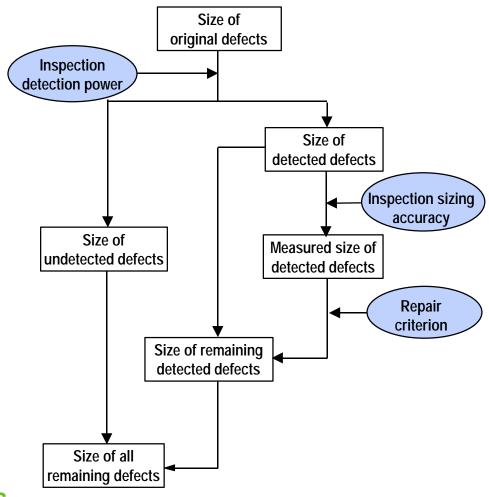
- **Maintenance impact**
  - Reduce number of defects per unit line length
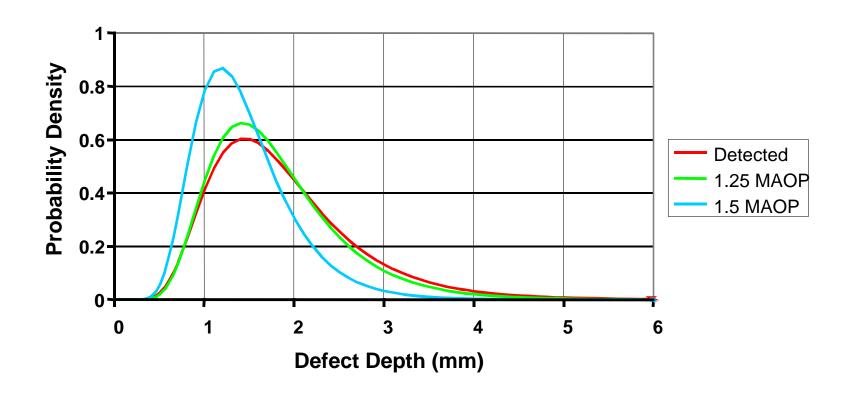 - Shift defect size distribution toward smaller values

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Quantifying Effect of Maintenance
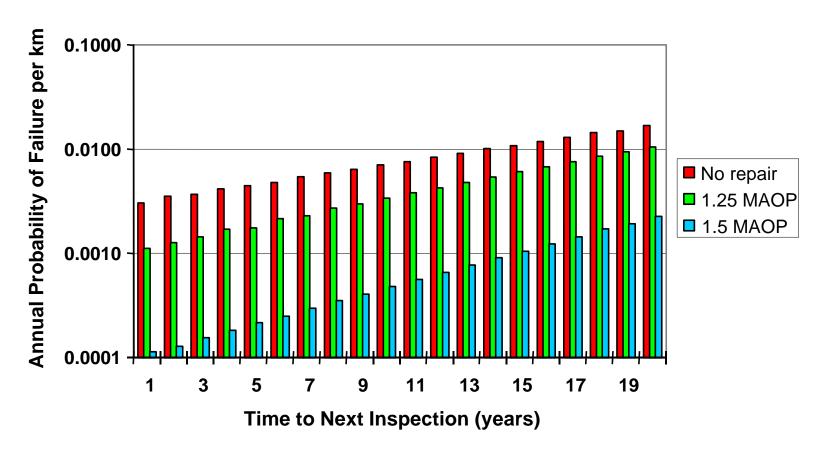
Modified Defect Size Distributions

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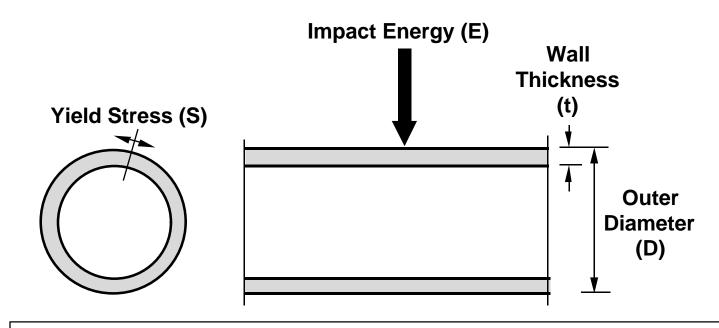
Effect on Probability

Application to Mechanical Damage

Impact Energy (E)

Wall Thickness (t)

Yield Stress (S)

Outer Diameter (D)
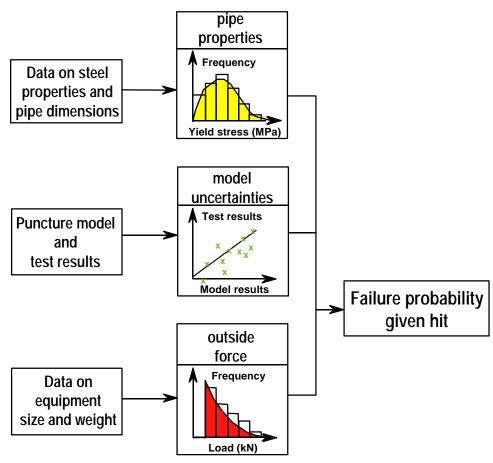
Failure probability = (No. line hits) x **(Failure probability per hit)**
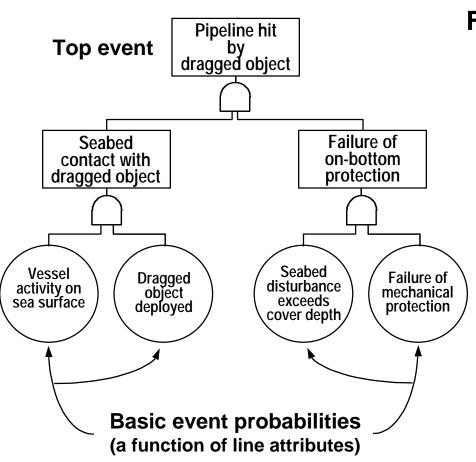
Probability of Failure Given Hit

pipe properties

Frequency

Yield stress (MPa)

Data on steel properties and pipe dimensions

model uncertainties

Test results

Model results

Puncture model and test results

outside force

Frequency

Load (kN)

Data on equipment size and weight

Failure probability given hit

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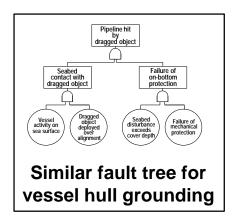
Frequency of Line Hits

Top event

**Fault Tree Model
(inductive logic)**

**Basic event probabilities
(a function of line attributes)**

**Similar fault tree for
vessel hull grounding**

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Effect of Maintenance

- **Mitigation philosophy**
  - **Prevent potential line hits**
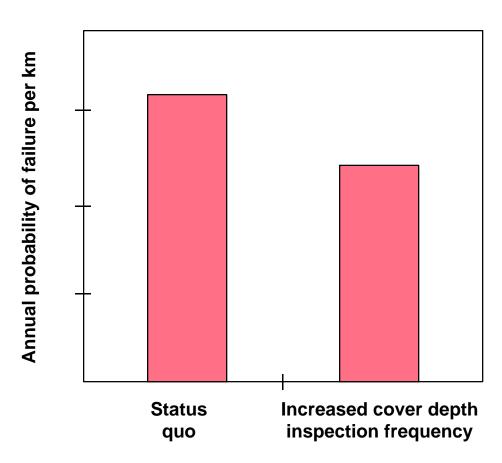
- **Example prevention options**
  - **Enhance awareness of pipeline location**
  - **Modify cover depth inspection frequency**
  - **Increase pipeline burial depth**
  - **Introduce mechanical protection**

- **Prevention Impact**
  - **Modify fault tree basic event probabilities**
  - **Reduce hit probability**

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Effect on Failure Probability

Status quo | **Increased cover depth inspection frequency**

Annual probability of failure per km

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Structural Reliability Approach - Summary

- **Calculate failure probability from**

  - **Structural behaviour models**

  - **Line and ROW information**

    - **Defect information (corrosion / SCC/ cracks / dent-gouges)**

    - **External forces (ground movement / mechanical damage)**

- **Suitable for maintenance optimization**

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Consequence Estimation Approach

Consequence measures

Category		Measure
Financial impact	→	Dollars
Public safety impact	→	Number of people at risk
Environmental impact	→	Effective residual spill volume
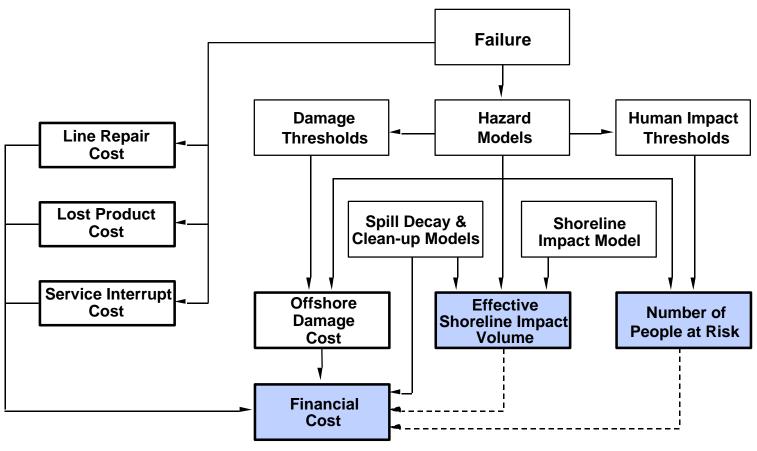
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Consequences of Pipeline Failure

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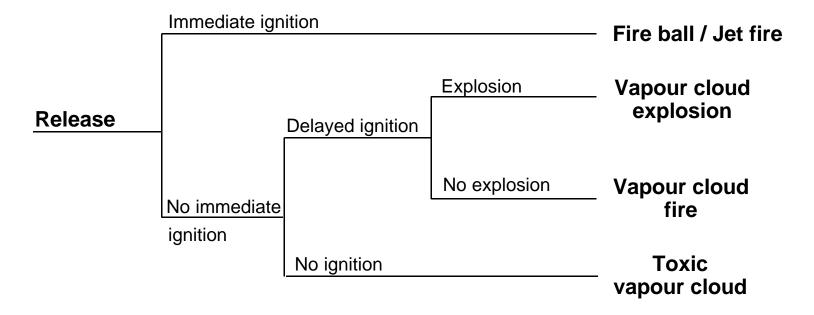
Consequences of Acute Release Hazards

Step 1 - Use event tree analysis (logic model) to estimate relative likelihood of all conceivable release hazards
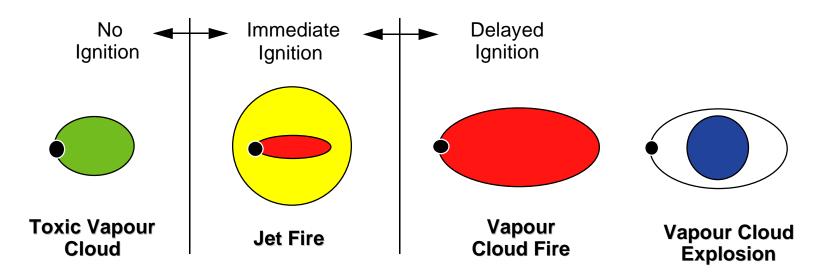
Immediate ignition — **Fire ball / Jet fire**

Release

Delayed ignition
- Explosion — **Vapour cloud explosion**
- No explosion — **Vapour cloud fire**

No immediate ignition

No ignition — **Toxic vapour cloud**

Consequence Analysis

Consequence of Acute Release Hazards

Step 2 - **Use hazard characterization models to estimate size of affected areas**

No
Ignition

Immediate
Ignition

Delayed
Ignition

**Toxic Vapour
Cloud**

Jet Fire

**Vapour
Cloud Fire**

**Vapour Cloud
Explosion**

Step 3 - **Estimate offshore damage cost**
(no. involved structures & vessels x property value)
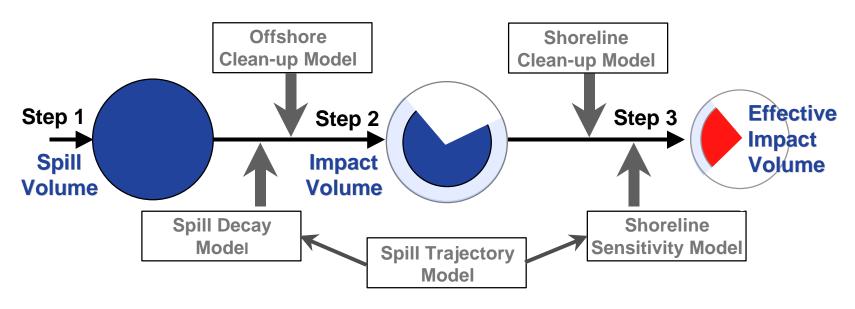**Estimate number of people at risk**
(no. involved structures & vessels x crew size)

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Consequence Analysis

Long-term Consequences of Product Release Hazard

Step 4 -   Assess clean-up costs
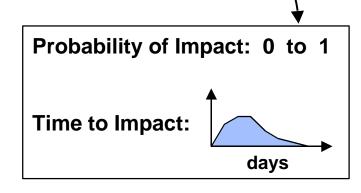   Estimate degree of natural resource damage

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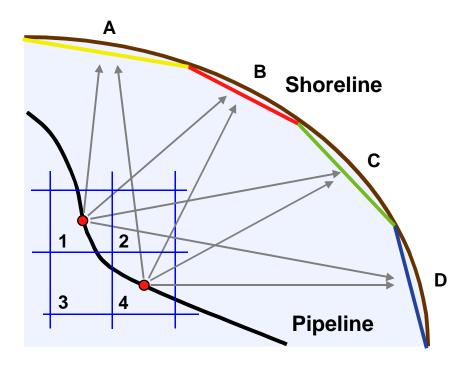
Spill Trajectory Model

Trajectory Analysis Results

Shoreline

	A	B	C	D
1				
2		#		
3				
4				

Launch Zone

Probability of Impact: 0 to 1

Time to Impact:

days

Spill Trajectory Analysis

A

B
Shoreline

C

D

Pipeline

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Software

PIRAMID™

PIPELINE RISK ANALYSIS FOR MAINTENANCE & INSPECTION DECISIONS

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PIRAMID Structure

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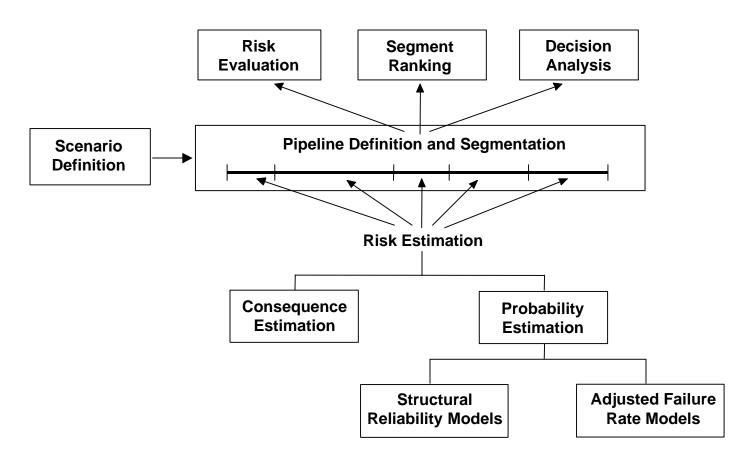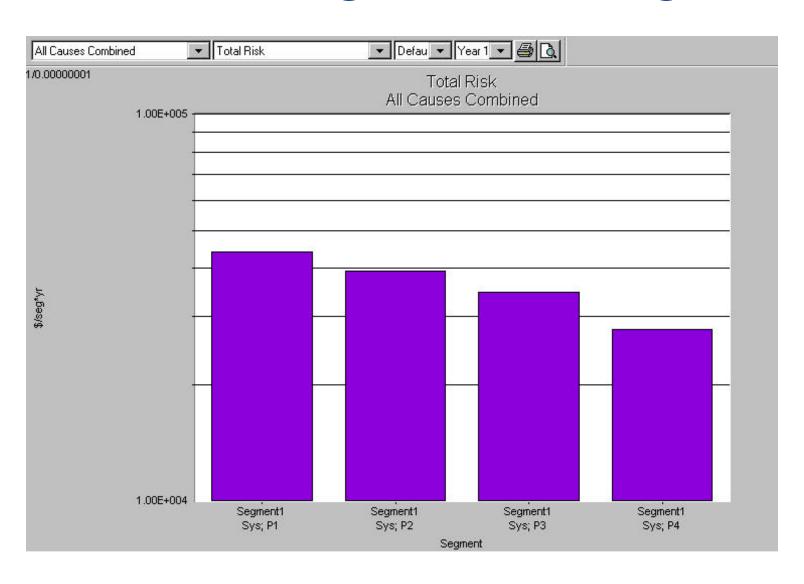
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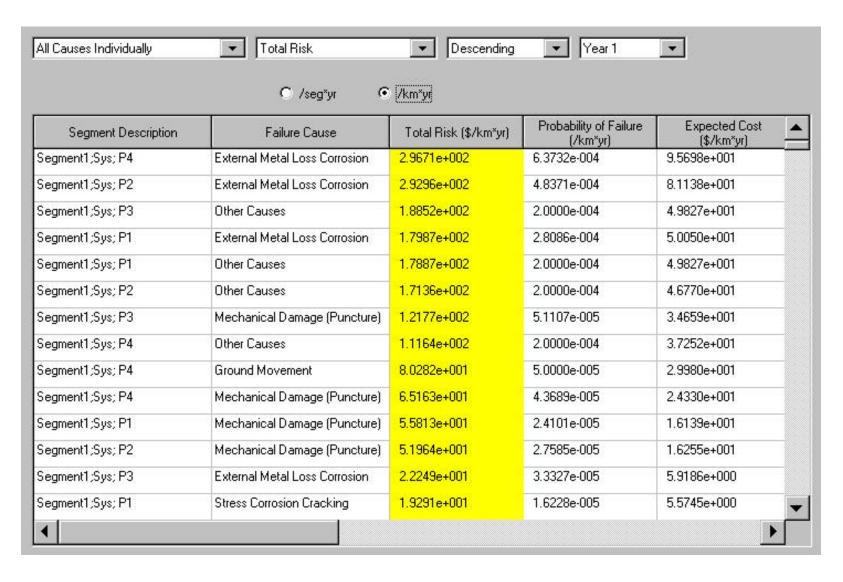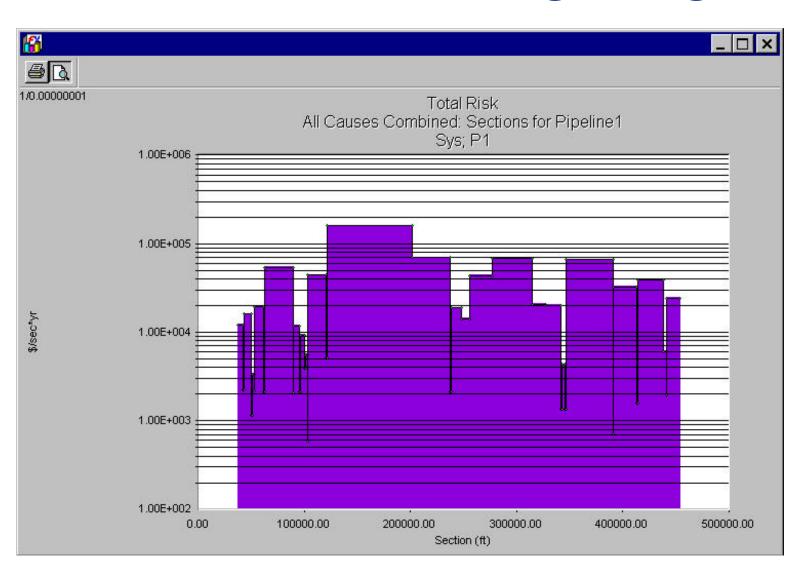
Segment Ranking Chart

Segment Ranking Table

All Causes Individually ▼	Total Risk ▼	Descending ▼	Year 1 ▼

○ /seg*yr   ◉ /km*yr

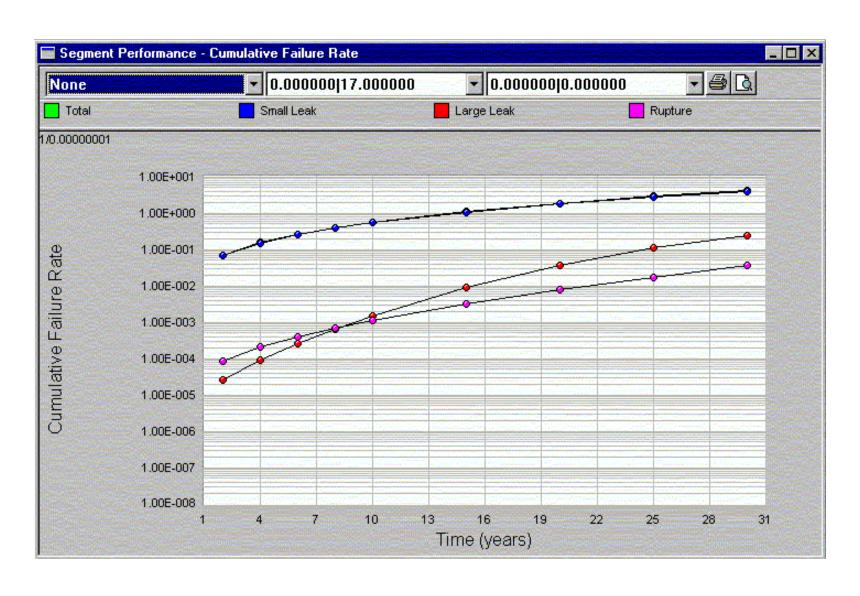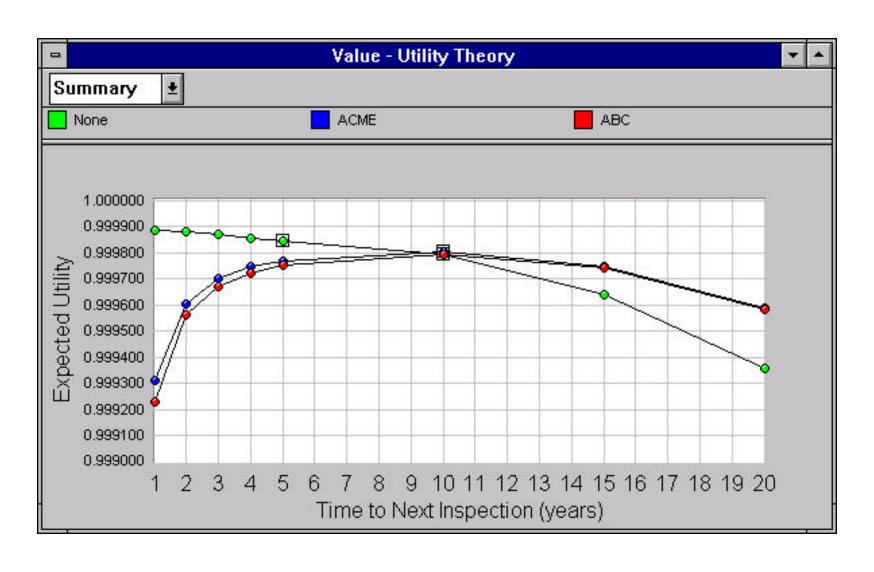| Segment Description	Failure Cause	Total Risk ($/km*yr)	Probability of Failure (/km*yr)	Expected Cost ($/km*yr)
Segment1;Sys; P4	External Metal Loss Corrosion	2.9671e+002	6.3732e-004	9.5698e+001
Segment1;Sys; P2	External Metal Loss Corrosion	2.9296e+002	4.8371e-004	8.1138e+001
Segment1;Sys; P3	Other Causes	1.8852e+002	2.0000e-004	4.9827e+001
Segment1;Sys; P1	External Metal Loss Corrosion	1.7987e+002	2.8086e-004	5.0050e+001
Segment1;Sys; P1	Other Causes	1.7887e+002	2.0000e-004	4.9827e+001
Segment1;Sys; P2	Other Causes	1.7136e+002	2.0000e-004	4.6770e+001
Segment1;Sys; P3	Mechanical Damage (Puncture)	1.2177e+002	5.1107e-005	3.4659e+001
Segment1;Sys; P4	Other Causes	1.1164e+002	2.0000e-004	3.7252e+001
Segment1;Sys; P4	Ground Movement	8.0282e+001	5.0000e-005	2.9980e+001
Segment1;Sys; P4	Mechanical Damage (Puncture)	6.5163e+001	4.3689e-005	2.4330e+001
Segment1;Sys; P1	Mechanical Damage (Puncture)	5.5813e+001	2.4101e-005	1.6139e+001
Segment1;Sys; P2	Mechanical Damage (Puncture)	5.1964e+001	2.7585e-005	1.6255e+001
Segment1;Sys; P3	External Metal Loss Corrosion	2.2249e+001	3.3327e-005	5.9186e+000
Segment1;Sys; P1	Stress Corrosion Cracking	1.9291e+001	1.6228e-005	5.5745e+000

Risk Variations Along a Segment

Failure Rate Versus Time

Decision Analysis - Utility Chart

Summary

- **Comprehensive user-friendly approach for risk-based integrity maintenance planning**

- **Quantitative and objective methodology**
  - **Historical incident data**
  - **Analytical models for**
    - **pipeline failure prediction**
    - **release hazard characterization**
  - **Pipeline condition data**

- **Benefits**
  - **Generates line-specific risk estimates**
  - **Quantifies the impact of maintenance actions**
  - **Identifies minimum cost solutions**

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